hep-ph/0411030

Testing the see-saw mechanism at collider energies

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Abstract

We propose a low energy extension of the Standard Model consisting of an additional gauged $U(1)_{B-L}$ plus three right-handed neutrinos. The lightest right-handed neutrinos have TeV scale masses and may be produced at colliders via their couplings to the Z_{B-L} gauge boson whose mass and gauge coupling is constrained by the out-of-equilibrium condition leading to upper bounds on the right-handed neutrino and Z_{B-L} production cross-sections at colliders. We propose a brane-world scenario which motivates such TeV mass right-handed neutrinos. Our analysis opens up the possibility that the mechanism responsible for neutrino mass is testable at colliders such as the LHC or VLHC.

November 2, 2004

1 Introduction

The see-saw mechanism [1],[2] is an attractive mechanism for accounting for light neutrino masses. The mechanism works by introducing right-handed neutrinos with "large" Majorana masses, which violate lepton number L, and the Yukawa couplings between the left-handed leptons and right-handed neutrinos then results in small effective Majorana mass operators for left-handed neutrinos. Such a scenario has potentially important cosmological implications for the baryon asymmetry of the universe via a mechanism known as leptogenesis [3]. It is clear that the see-saw mechanism satisfies the Sakharov conditions of lepton number violation, and CP violation due to the complex neutrino Yukawa couplings. Providing the out-of-equilibrium condition is also met when the right-handed neutrinos decay, a net lepton number L may then be generated which may subsequently be converted into a net baryon number B by sphaleron interactions which preserve $B - L$.

Given the recent progress in neutrino physics, there has been much discussion concerning both the see-saw mechanism [4] and leptogenesis [5]. In the simplest implementations of thermal leptogenesis the re-heat temperature after inflation must be in excess of the lower bound arising from gravitino production [6]. [1] Typically thermal leptogenesis works best when the lightest right-handed neutrino mass exceeds about 10^9 GeV, while in order to avoid excessive thermal production of gravitinos the temperature of the universe after inflation must not exceed this value. Even ignoring the gravitino problem, such large values of right-handed neutrino masses make them inaccessible to experiment at planned or even imagined collider energies. Testing the see-saw mechanism experimentally in any direct way therefore seems virtually impossible under the thermal leptogenesis framework.

A possible solution to the gravitino problem is provided by the idea of resonant

[1] In the type II see-saw mechanism this conflict can be somewhat ameliorated [7].

leptogenesis [8]. The key observation of resonant leptogenesis is that, if the lightest two right-handed neutrinos are closely degenerate, then resonance effects can enhance the production of lepton number even for a right-handed neutrino mass scale as low as a TeV, allowing the reheat temperature to be low enough to avoid the gravitino problem. [2]

With such light right-handed neutrinos one may think it possible to test the see-saw mechanism experimentally at collider energies. However in the absence of additional interactions this is not the case since, even if TeV mass right-handed neutrinos are kinematically accessible to high energy colliders such as the LHC, their Yukawa couplings are necessarily so weak as to render their production cross-section unobservable.

In this paper we propose a minimal scenario in which, in addition to having light right-handed neutrinos, there is also a low energy gauged $B-L$ symmetry $U(1)_{B-L}$. [3] It is natural that the scale of gauged $B-L$ symmetry breaking should be somewhat higher than the heaviest right-handed neutrino mass, since gauged $B-L$ symmetry forbids Majorana neutrino masses. Cancellation of gauged $B-L$ anomalies requires that there should be three right-handed neutrinos. If we assume the lightest pair of right-handed neutrinos to be degenerate, we would therefore expect that the third right-handed neutrino mass M_3 to be closer to the mass scale of $B-L$ symmetry breaking v_{B-L}, which is somewhat higher than the lightest right-handed neutrinos mass scale M_1. We are therefore led to propose a new low energy extension of the Standard Model consisting of an additional gauged $U(1)_{B-L}$ plus three right-handed

[2]If supersymmetry (SUSY) is additionally assumed then TeV mass right-handed neutrinos allow the possibility that the soft SUSY breaking mass parameters may be at least partly responsible for leptogenesis and radiatively generated neutrino masses [9]. The present analysis can be extended for this case.

[3]In general the extra $U(1)$ could be some linear combination of $B-L$ and hypercharge Y. The vector space spanned by these generators includes the third generator of $SU(2)_R$, T_{3R}, and the $U(1)_X$ generator X contained in the maximal $SO(10)$ subgroup $SU(5)\times U(1)_X$. But here we focus on the case of an extra $U(1)_{B-L}$ for simplicity and definiteness.

neutrinos with the following new mass scales: $M_1 \lesssim M_2 \lesssim M_3 \lesssim v_{B-L}$, with a possible accurate degeneracy involving the lightest right-handed neutrino pair.

The main goal of this paper is to discuss the collider phenomenology of light right-handed neutrinos and Z_{B-L} gauge bosons, constrained by the out-of-equilibrium conditions as required by thermal leptogenesis. [4] We shall require the effective leptogenesis neutrino mass parameter to be $\tilde{m}_1 \sim 10^{-3}$ eV for efficient production and out-of-equibrium decay of the right-handed neutrinos $N_{1,2}$. [5] The requirement that the lightest right-handed neutrino pair be out-of-equilibrium when they decay implies that the $B-L$ interactions must be sufficiently weak, leading to a lower bound on v_{B-L} or an upper bound on the gauge coupling g_{B-L}, depending on the mass ordering of M_1 and M_{B-L}. These bounds in turn leads to upper limits on the production cross-section for right-handed neutrinos and Z_{B-L} gauge bosons at colliders, which we shall also discuss. We shall also explore the theoretical motivation for TeV mass right-handed neutrinos, and propose a specific brane-world scanario.

2 Out-of-equilibrium Condition

2.1 $M_{B-L} \gg M_1$

We shall begin by assuming that $M_{B-L} \gg M_1$, and show that the out-of-equilibrium condition leads to a lower bound on v_{B-L} in this case.

The lightest right-handed neutrinos must decay while they are out-of-equilibrium in the early Universe. We have already assumed that the direct decays of right-handed neutrinos are always out-of-equilibrium, consistent with $\tilde{m}_1 \sim 10^{-3}$ eV, so

[4] Note that above its breaking scale v_{B-L} the presence of exact gauged $B-L$ means that the net $B-L$ of the universe must be exactly zero. Since $B+L$ is violated by sphaleron interactions this implies that baryogenesis or leptogenesis cannot occur above the scale v_{B-L}.

[5] Our scenario should not be confused with a recently discussed scenario in which low energy leptogenesis occurs due to scattering from domain walls produced by the breaking of a discrete left-right symmetry, and the right-handed neutrinos are constrained not to erase the $B-L$ [10].

that we only need additionally ensure that the new Z_{B-L} interactions do not bring the lightest right-handed neutrinos back into thermal equilibrium. [6] The reaction rate of right-handed neutrinos is given by:

$$\Gamma =< \sigma_{ann} n v > \tag{1}$$

where σ_{ann} is the total annihilation cross-section of lightest right-handed neutrinos into three families of Standard Model fermions (f) and antifermions $(\bar{f})$, and n is the number density of right-handed neutrinos. [7] The annihilation cross-section σ_{ann} is given by:

$$\sigma_{ann} = \sigma(N_1 N_1 \rightarrow \sum_f f\bar{f}) \tag{2}$$

due to the tree-level exchange of a $B-L$ gauge boson of mass M_{B-L} with a gauge coupling g_{B-L},

$$\sigma(N_1 N_1 \rightarrow \sum_f f\bar{f}) \sim 3 \times \frac{13}{3} \frac{g_{B-L}^4}{48\pi} \frac{E^2}{M_{B-L}^4} \sim \frac{1}{4\pi} \frac{E^2}{v_{B-L}^4} \tag{3}$$

where the mass of the gauge boson is given by $M_{B-L} = g_{B-L} v_{B-L}$. The number density of right-handed neutrinos n given by:

$$n = \frac{3}{4} \frac{2.404}{2\pi^2} g \left(\frac{kT}{\hbar c}\right)^3 \sim \frac{1}{\pi^2} T^3 \tag{4}$$

setting $\hbar = c = k = 1$.

To generate lepton number asymmetry, the right-handed neutrinos must be out-of-equilibrium when they decay. If they decay at a temperature $E \sim T \sim M_1$ then their reaction rate when they decay is given from Eqs.(1,3,4) by

$$\Gamma =< \sigma_{ann} n v >\sim \frac{1}{4\pi} \frac{E^2}{v_{B-L}^4} . \frac{1}{\pi^2} T^3 \sim \frac{1}{4\pi^3} \frac{M_1^5}{v_{B-L}^4}. \tag{5}$$

[6] Note that the new Z_{B-L} interactions do not violate lepton number by themselves. However since the right-handed neutrinos are Majorana particles, such Z_{B-L} interactions (with unsuppressed L-violating mass insertions) would bring the right-handed neutrinos in the thermal equibrium with vanishing chemical potential unless they are out of equilibrium.

[7] Note that the annihilation cross-section is the most relevant one for satisfying the out-of-equilibrium condition. We have also assumed that scalar fermions are heavier than the right-handed neutrinos N_1 and N_2.

To be out-of-equilibrium the reaction rate be less than the Hubble constant H whose square at a temperature T is given by

$$H^2 \approx \frac{8\pi}{3} G_N \rho \sim \frac{4\pi^3}{45} \frac{g^* T^4}{M_P^2} \sim 3 \frac{g^* T^4}{M_P^2} \tag{6}$$

setting $\hbar = c = k = 1$ where g^* is the total number of degrees of freedom at the temperature T and M_P is the Planck mass $M_P \approx 1.2 \times 10^{19}$ GeV. The out-of-equilibrium condition is given by $\Gamma < aH$ at $E \sim T \sim M_1$, where $a \sim O(10)$, which from Eqs.(5,6) leads to the lower bound on v_{B-L}:

$$v_{B-L} > \left(\frac{M_P}{4\pi^3 a \sqrt{3g^*}} \right)^{1/4} M_1^{3/4} \sim 10^6 \text{ GeV} \left(\frac{M_1}{1 \text{ TeV}} \right)^{3/4} . \tag{7}$$

Eq.(7) tells us that for a degenerate pair of right-handed neutrinos of mass 1 TeV the scale of $B - L$ breaking must exceed 10^6 GeV.

2.2 $M_{B-L} \lesssim 2M_1$

We now consider the case that $M_{B-L} \lesssim 2M_1$, and show that the out-of-equilibrium condition leads to an upper bound on g_{B-L} in this case.

In this case the estimate in Eq.(3) becomes

$$\sigma(N_1 N_1 \to \sum_f f\bar{f}) \sim 3 \times \frac{13}{3} \frac{g_{B-L}^4}{48\pi} \frac{1}{16E^2} \sim \frac{1}{4\pi} \frac{g_{B-L}^4}{16E^2}. \tag{8}$$

The resulting reaction rate at $E \sim T \sim M_1$ in Eq.(5) becomes modified to

$$\Gamma = < \sigma_{ann} n v > \sim \frac{1}{4\pi^3} \left(\frac{g_{B-L}}{2} \right)^4 M_1. \tag{9}$$

The out-of-equilibrium condition is given by $\Gamma < aH$ at $E \sim T \sim M_1$, where $a \sim O(10)$, which from Eqs.(9,6) leads to the upper bound on g_{B-L}:

$$g_{B-L} < 2 \times \left[4\pi^3 a \sqrt{3g^*} \left(\frac{M_1}{M_P} \right) \right]^{1/4} \sim 2 \times 10^{-3} \left(\frac{M_1}{1 \text{ TeV}} \right)^{1/4} . \tag{10}$$

Other reactions are important at $E \sim T \sim M_1$ for the case $M_{B-L} < 2M_1$, for example real Z_{B-L} pair production and annihilation: $N_1 N_1 \leftrightarrow Z_{B-L} Z_{B-L}$ whose cross-section will be of similar magnitude to that in Eq.(8).

For $M_{B-L} \sim 2M_1$ at $E \sim T \sim M_1$ it becomes possible to have single Z_{B-L} production and decay: $Z_{B-L} \leftrightarrow f\bar{f}$ (including N_1N_1). This special case leads to a quite different bound on the gauge coupling since the decay rate of Z_{B-L} is given by:

$$\Gamma(Z_{B-L} \to \sum_f f\bar{f}) \sim 3 \times \frac{13}{3}\frac{g_{B-L}^2}{48\pi}M_1 \sim \frac{1}{4\pi}g_{B-L}^2 M_1. \tag{11}$$

The out-of-equilibrium condition in this case is obtained by comparing the decay rate in Eq.(11) to the Hubble expansion rate $\Gamma < aH$ at $E \sim T \sim M_1$, where $a \sim O(10)$, which from Eqs.(11,6) leads to the upper bound on g_{B-L}:

$$g_{B-L} < \sqrt{4\pi a}(3g^*)^{1/4}\left(\frac{M_1}{M_P}\right)^{1/2} \sim 10^{-6}\left(\frac{M_1}{1\ \text{TeV}}\right)^{1/2}. \tag{12}$$

In this special case when $M_{B-L} \sim 2M_1$ the bound on the gauge coupling in Eq.(12) is much more stringent than the bound on the gauge coupling in Eq.(10) for the more general case $M_{B-L} < 2M_1$.

Finally we should note that the upper bound on g_{B-L} is obtained even for the case, $M_{B-L} \lesssim 10M_1$. For $M_{B-L} > M_1$ the inverse decay has a Boltzmann suppression $e^{M_{B-L}/T}$ with $T \simeq M_1$. The Boltzmann factor is only 10^{-3} for $M_{B-L} \simeq 10M_1$ and hence we may have still a strigent bound on g_{B-L}^2 but weaker than the case $M_{B-L} \sim 2M_1$. So the bound on v_{B-L} is given when $M_{B-L} \gtrsim 20 \times M_1$ since the Boltzmann factor is 10^{-6} and the inverse decay of Z_{B-L} becomes negligible compared with the $B-L$ gauge exchanges.

3 Phenomenology

For the case of a heavy Z_{B-L}, $M_{B-L} \gg M_1$, the typical cross-section for production of the lightest right-handed neutrinos at colliders is given from Eq.(3) and bounded from Eq.(7) by

$$\sigma(e^+e^- \to N_1N_1) < \frac{1}{48\pi}\frac{E^2}{10^{24}\ \text{GeV}^4}\left(\frac{1\ \text{TeV}}{M_1}\right)^3 \sim 3 \times 10^{-9}\ \text{fb}\left(\frac{E}{1\ \text{TeV}}\right)^2\left(\frac{1\ \text{TeV}}{M_1}\right)^3 \tag{13}$$

where we have used the conversion 1 GeV$^{-2} \approx 4 \times 10^{-4} b$. Unfortunately the cross-section may be too small to enable right-handed neutrinos to be produced at TeV energies such as the LHC or CLIC. For efficient production of right-handed neutrinos a collider with an energy approaching the mass of the $B-L$ gauge boson $M_{B-L} = g_{B-L} v_{B-L}$ would be required, such as the VLHC for example. Although the right-handed neutrinos are produced in pairs via their Z_{B-L} couplings, they will decay singly via their small Yukawa couplings into either (left-handed) neutrino plus Higgs h^0, or charged lepton plus (longitudinal) W, with a characteristic signature in both cases. The expected decay rate for TeV mass right-handed neutrinos with a Yukawa coupling about 10^{-6} would be $\Gamma(N_1 \to HL) \approx 10^{-10}$ GeV corresponding to a lifetime of about 10^{-14}s.

Turning to the other possibility of a lighter Z_{B-L}, with $M_{B-L} < 2M_1$, from Eq.(10) we see that the gauge coupling must be smaller than about 10^{-3} for TeV scale right-handed neutrinos. This also leads to a cross-section for right-handed neutrinos at colliders bounded by

$$\sigma(e^+e^- \to N_1 N_1) < 4 \times 10^{-7} \text{ fb} \left(\frac{1 \text{ TeV}}{E}\right)^2 \left(\frac{M_1}{1 \text{ TeV}}\right). \tag{14}$$

Unlike the cross-section in Eq.(13), the cross-section in Eq.(14) is suppressed at higher energies. However, in this case one might hope to produce real on-shell Z_{B-L} with mass below the TeV scale. The Z_{B-L} may be produced singly by mechanisms which involve only two powers of g_{B-L} in the rate, and so the typical production cross-sections are expected to be enhanced relative to that in Eq.(14) by a factor of about a million. For example the Z_{B-L} may be produced singly by the Drell-Yan process, and may be discovered via its decays into e^+, e^-, μ^+, μ^-, or jet-jet. The discovery limits for such a Z' at the LHC have been studied by ATLAS, and for example a TeV mass Z' may be discovered at the 5σ level with $100 fb^{-1}$ providing the square of the gauge coupling is about 10^{-3} [11]. With the small gauge coupling bounded in Eq.(10), discovery at the LHC will be clearly difficult, but since this bound is independent of the mass of the Z_{B-L}, which may be as light as the ordinary Z for example, its discovery may be possible in principle at the LHC. Note that the couplings of the $B-L$ gauge boson Z_{B-L} to leptons and quarks are 1:1/3, which may be tested if its decay is observed.

4 A Brane Scenario

In this section we address the following questions:

1. Why are the Yukawa couplings inducing the Dirac neutrino masses so small ? To get neutrino masses of order 10^{-2} eV with 1 TeV right-handed Majorana mass we need $M_{Dirac} \simeq 10^{-4}$ GeV. Thus the Yukawa coupling should be $\sim 10^{-6}$.

2. Is there a natural inflation model with reheat temperature $T_R \simeq$ a few TeV ? In other words, why do we assume $M_1 \simeq 1$ TeV in the estimates above? The constraint from the gravitino problem tells us only $T_R < 10^6$ GeV and hence M_1 could be as large as 10^6 GeV.

The answer to the second question is straighforward: lower-energy scale inflation may produce lower reheating temperature, in general. The new inflation model is a candidate for the low-energy scale inflation. One of us has constructed a new inflation model in SUGRA and found that the reheating temperature is given by $T_R \simeq m_{3/2} <$ few TeV [12].

Moreover, the low-energy scale inflation is favored in string landscape. The string theory may have a number of vacuua which may have many inflaton candidates. The vacuum which has many inflations is favored, since many inflations make larger universe. So it is better to have as lower-energy scale inflation as possible and it is likely that a new inflation is the last inflation we can see. [8]

The answer to the first question is not difficult also. Small right-handed neutrino masses at the TeV scale which require small Dirac Yukawa couplings in the range $10^{-5} - 10^{-6}$. To account for this we propose the following extra-dimensional set up consisting of two parallel 3-branes where the standard model fermions and Higgs are on one brane, and the right-handed neutrinos are on the other brane, and the $B - L$ gauge multiplet is in the bulk which contains n extra dimensions. The $B - L$ gauge interaction has 4 dimensional anomaly on the each branes, but it is cancelled by bulk Chern-Simons term [13]. The $B - L$ is broken by a Higgs vacuum expectation value v_{B-L} located on one of the 3-branes. The Yukawa coupling constant in this case is exponentially suppressed $Y_\nu \sim e^{-M_* L}$ where M_* is the cut-off (string) scale and L is the compactification scale of the extra dimension(s). Assuming $M_* L \sim 11 - 14$ can account for Dirac Yukawa couplings in the range $10^{-5} - 10^{-6}$.

In such a scenario the gauge coupling of the $B - L$ is given by

$$g_{B-L} \sim g_0 (M_* L)^{-n/2} \tag{15}$$

Assuming $g_0 \sim 0.3$ and $M_* L \sim 12$ we find $g_{B-L} \sim 2 \times 10^{-2}$ for $n = 2$ which implies the $B - L$ gauge boson mass $M_{B-L} \sim 20$ TeV for $v_{B-L} \simeq 10^6$ GeV. For n=6 we find $g_{B-L} \sim 2 \times 10^{-4}$, which is in the appropriate range for the light Z_{B-L} scenario

5 Conclusion

We have proposed a low energy extension of the Standard Model consisting of an additional gauged $U(1)_{B-L}$ plus three right-handed neutrinos where the lightest right-handed neutrino mass scale is $M_1 \gtrsim 1$ TeV. In the absence of SUSY, this requires resonant leptogenesis with the lightest right-handed neutrino pair being approximately degenerate.

[8] T.Y. thanks K.-I. Izawa for the discussion of inflation models on the string landscape.

We have discussed the collider phenomenology of light right-handed neutrinos and Z_{B-L} gauge bosons, constrained by the out-of-equilibrium conditions. We find that for $M_{B-L} \gg M_1$ there is a lower limit on the symmetry breaking scale v_{B-L}, while for $M_{B-L} \lesssim 2M_1$ there is an upper limit on the gauge coupling g_{B-L}. Although the TeV mass right-handed neutrinos may be produced at colliders via their couplings to the Z_{B-L} gauge bosons, the above limits severely constain the production cross-sections of both right-handed neutrinos and Z_{B-L} gauge bosons at colliders.

We have also considered the theoretical motivation for TeV scale right-handed neutrinos coming from brane-world set-ups and string theory. We have proposed a particular brane-world scenario in which small Yukawa couplings emerge, with a $B-L$ gauge coupling and mass in the appropriate ranges consistent with the bounds from thermal leptogenesis, depending on the number of extra dimensions. For two extra dimensions the mass of the Z_{B-L} gauge boson is expected to have a mass $M_{B-L} \sim 20$ TeV. The cross-section for production of right-handed neutrinos is expected to become observable in this case when the centre of mass energy of the collider approaches M_{B-L}, which motivates a future collider such as the VLHC. For six extra dimensions the Z_{B-L} gauge boson could be as light as the ordinary Z boson with a cross-sections for production that will make its discovery at the LHC challenging.

In conclusion, the possibility of TeV mass right-handed neutrinos, together with additional Z_{B-L}, is cosmologically consistent from the point of view of leptogenesis, and has some theoretical motivation from string theory and extra dimensions. It would open up the possibility of testing the mechanism responsible for neutrino mass experimentally at collider energies corresponding to the LHC or a future VLHC.

Acknowledgments

We would like to thank the organisers of the Nobel Symposium 129 on Neutrino Physics where this work was begun. S.K. thanks Stefan Antusch for useful comments.

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